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ION CYCLOTRON RESONANT HEATING (ICRH) SLOT ANTENNA FOR THE TANDEM MIRROR EXPERIMENT UPGRADE (TMX-U)

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ION CYCLOTRON RESONANT HEATING SLOT ANTENNA
FOR THE TANDEM MIRROR EXPERIMENT-UPGRADE*

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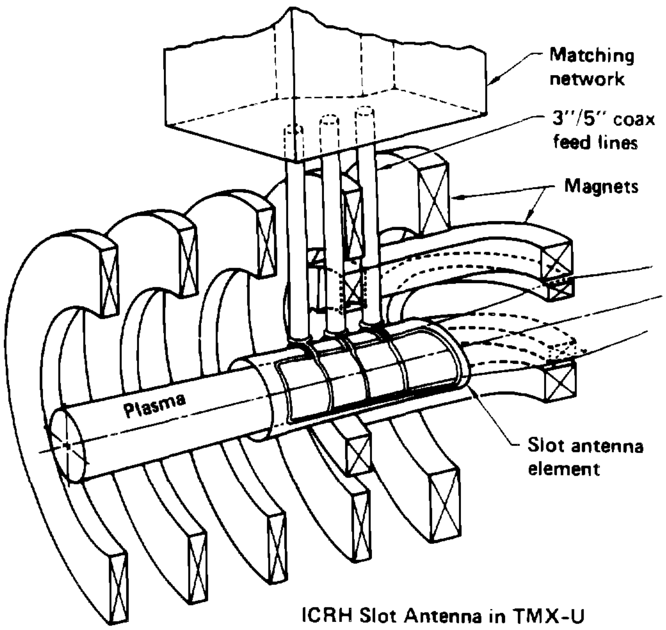
Abstract

The Ion Cyclotron Resonant Heating (ICRH) slot antenna has been a part of the ion and electron plasma heating system in the central cell region of the Tandem Mirror Experiment-Upgrade (TMX-U). This paper presents the mechanical design and arrangement of the antenna, coax feed lines, feedthroughs, and matching network for the slot antenna.

This antenna is a slotted, hollow tube that completely surrounds and conforms to the plasma shape in the east end of the central cell region. The shell is made of copper sheet with 1-inch-diameter copper tubing leads. The three feed lines are coax pipe with 3-inch inner and 5-inch outer conductors. The three feedthroughs are a triaxial design for high radio frequency (RF) voltages and currents of 30 kV and 700 amps peak, respectively. The antenna can be fed in either a full-wave mode or a half wave mode depending on the strapping configuration to the three feedthroughs.

The capacitor matching network is external to the vacuum chamber. It consists of two remotely controllable capacitors, variable from less than 100 to 1800 pF, and six 1000-pF fixed capacitors that can also be remotely switched into and out of the circuit. There are also provisions for up to ten additional fixed capacitors in the system.

The antenna has been operated to power levels in excess of 300 kW.



ICRH Slot Antenna in TMX-U

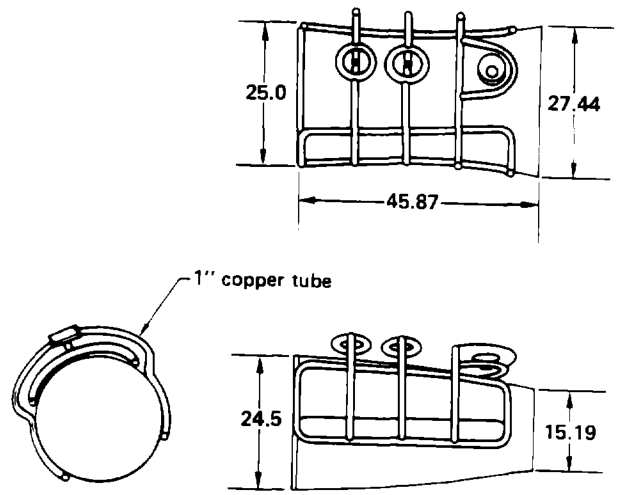
Figure 1.

Introduction

The slot antenna is located in the east end of the central cell region and extends from the circular axisymmetric region into the elliptical transition region (Fig. 1). The z location, as measured from the midplane of the machine, is from -146 cm to -260 cm and the magnetic field varies from 4.05 kG to 5.92 kG. The four major parts of this system include: 1) antenna element, 2) coax feed lines, 3) feedthroughs, and 4) external matching network. The physics concepts which specified the design criteria are presented in the paper by W. F. Cummins.[1]

Antenna Element

This antenna is a slotted, hollow tube that completely surrounds and conforms to the plasma shape. The shell is made of 0.062-inch thick copper sheet with 1-inch OD copper tubing around the slots. The 1-inch tubing is also used to form the three leadpairs from the slots to the top of the antenna where the connections are made to the main coax feed lines (see Figs. 2,3). The slots and top of the antenna were rotated 22.5 degrees from the vertical so that the coax lines would miss the magnet structure and have shorter paths to the available vacuum ports.



ICRH Slot Antenna Assembly

Figure 2.

The fabrication of the antenna was done by the sheet metal shop at Lawrence Berkeley Laboratory (LBL). A prototype full-scale testing model had previously been constructed by our shops; therefore, the basic ideas for making this odd-shaped antenna had already been developed. An accurate match to the plasma cross section was obtained by forming the sheet over seven aluminum templates which were machined on a NC mill. The 1-inch tube-to-sheet-metal joint was brazed with an 84% copper and 6% silver alloy, which minimized the heat that could cause warping. Although the manufacturer recommended torch brazing, LBL found

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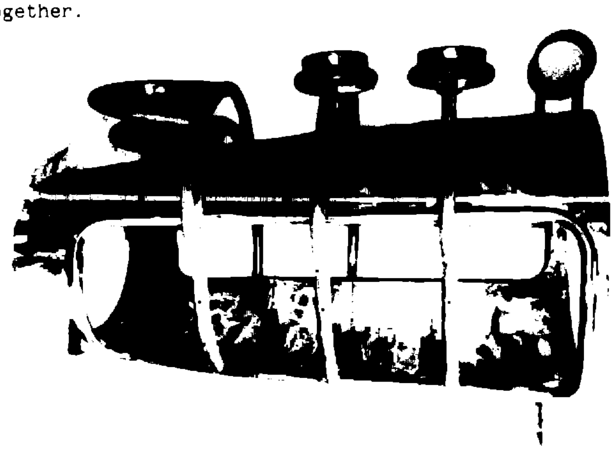
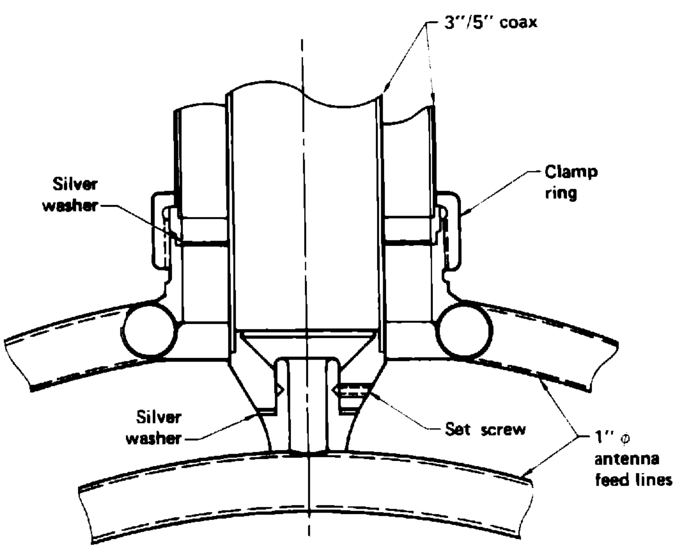
it was easier and more effective to use a TIG welder with the braze rod. This particular braze material was also chosen because it required no flux material to facilitate joining. Since this antenna would be close to the plasma, this procedure provided a better quality vacuum outgassing surface and, therefore, less contamination to the plasma.

The connections from the 1-inch-diameter antenna rings to the 3-inch-and 5-inch-diameter coax feed lines required smooth transitions from one diameter to the next and also required good RF current connections. The ability to easily assemble and disassemble them resulted in the design shown in Fig. 4. The internal line incorporated a three-point set screw arrangement for assembly. This forced the two surfaces together without the need for twisting of the coax or antenna. A 0.010-inch-thick silver washer was placed between the joining surfaces to provide better RF contact. The external 5-inch line was connected by making a ring with the 1-inch antenna feed lines and welding a threaded transition piece to it. These mating surfaces also had a silver washer between them. A threaded stainless steel ring external to the 5-inch coax pressed these parts together.



ICRH Slot Antenna

Figure 3.



Antenna to Coax Connection Detail

Figure 4.

When these silver washer joints were inspected after use, it was apparent that there was not good contact completely around the circumference of the joint. However, there were no signs of arcing at these points during full-power runs. Currents of 1000 amps were experienced at these joints. Because of the apparently poor contact, however, these joints were redesigned when the new east loop antenna was installed [1].

This antenna also had copper plasma limiters at each of its ends (Fig. 5). These were bolted on to the ends with RF gaskets to insure good electrical contacts. Their purpose was to keep the plasma several centimeters away from the antenna to reduce power absorption by ions and electrons accelerated into the antenna structures. These limiters also extended outside the shell to protect the leads and coax from the halo plasma and, therefore, prevent arcing at these high-voltage points. These limiters also reduced long-wavelength excitation of the plasma from RF leakage fluxes at the ends of the antenna.

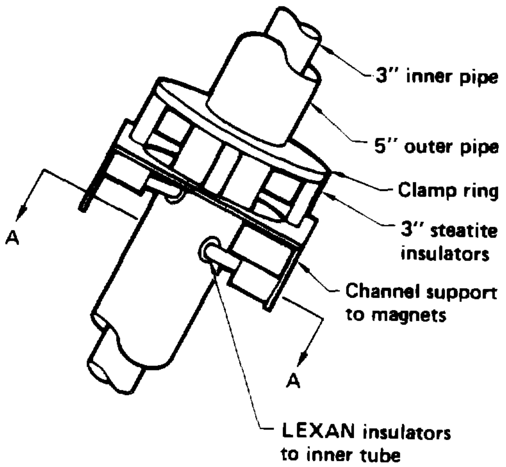
Coax Feed Lines

The coax feed lines are located inside the vacuum vessel between the antenna and vacuum feedthrough. The lines are made of copper pipe. The sizes chosen were 3-inch OD, 0.065-inch wall, and 5.125-inch OD, 0.125-inch wall pipe. There are three of these coax lines running from the antenna to the vacuum vessel wall.

These coax lines were designed around the following parameters: 1) have a 1-inch space between the inner and outer pipes with $\pm$ 1/8-inch tolerance to hold off the possible 50-kV potential between them, 2) be as large as possible in diameter to minimize inductance but still fit between the existing magnet structures, 3) keep the weight of each assembly as low as possible for ease in installation and for lower stresses on the support insulators, 4) have their own support structure, since neither the antenna nor the feedthroughs could support them or keep the inner and outer pipes centered with each other, 5) have both inner and outer pipes electrically isolated from each other and the rest of the machine, 6) allow no insulator material in the 1-inch gap between inner and outer pipe because of the high voltages between them (10 kV/inch along an insulator was used as a design value), 7) maintain a vacuum of at least 1.0×10^{-5} Torr in the 1-inch gap between inner and outer pipes, and 8) provide for thermal contraction of the pipes because they pass through two liquid-nitrogen panels at 77°K.

The 3-inch and 5-inch pipes were chosen because they were the most readily available pipes having the thinest wall that would allow a 1-inch spacing between them. These sizes were also the largest that would fit between the existing machine magnets. The configuration of the vessel and magnets required that these coax pipes have several bends in them. This did not allow the inner and outer pipes to be fabricated separately and then assembled together. Also, because of their sizes we found that they could not be bent as a coax assembly to the configuration needed. To fabricate them, therefore, we had to section and angle them and then join the sections by welding. This method gave us an annulus spacing of only 3/4" inch in places and produced some sharp edges between the inner and outer pipes that had to be ground down.

Since the coax had to have their own support structure and be electrically isolated from the machine, the designs in Figs. 6 and 7 were chosen.

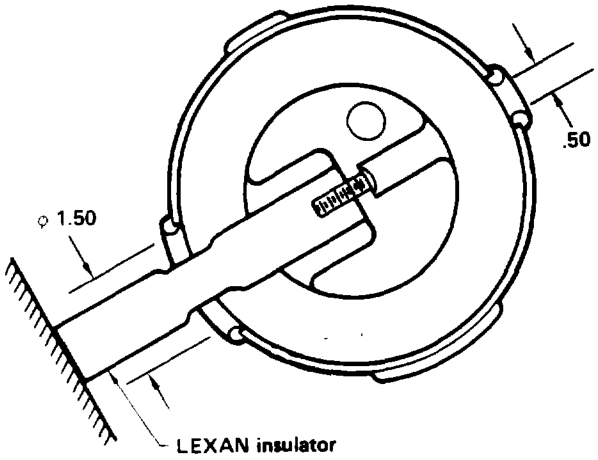


Coax Feed Line Supports

Figure 6.

As seen in Fig. 6 a clamp ring held the 5-inch pipe without deforming it. This ring then rested on a set of six 3-inch-long steatite insulators that were supported to the machine magnets. Because of the weight and angle of this assembly, two of these support systems were installed per coax. The insulators were stronger than calculated and later one set was removed. To support the inner pipe, 1.5-inch-diameter holes were put in the outer pipe so the two LEXAN insulators, positioned 90 degrees apart, could protrude through to an external support that was at machine ground (Fig. 7). A copper plug was made for the inner coax to hold the insulator. This plug had a hole through it to provide vacuum pumpout of the inner pipe. Copper rings, 1/4-inch in diameter, were brazed to the holes in the outer coax to minimize the voltage stresses. The LEXAN insulators were necked down at assembly because of misalignment errors between the inner and outer pipes. These insulators were 5 inches long in order to hold off 50-kV to ground. Later, because of the chance of carbon arc tracking, some of these LEXAN insulators were replaced with 5-inch-long, 3/4-inch-diameter alumina insulators. No carbon tracks were observed on the removed LEXAN insulators, however.

Calculations showed that to maintain the required vacuum of 1.0×10^{-5} Torr in the coax that only one additional 3/4-inch-diameter hole was required in the inner pipe between the support plugs. The other holes already required for the support insulators provided the remaining vacuum pumpout when molecular flow was assumed.

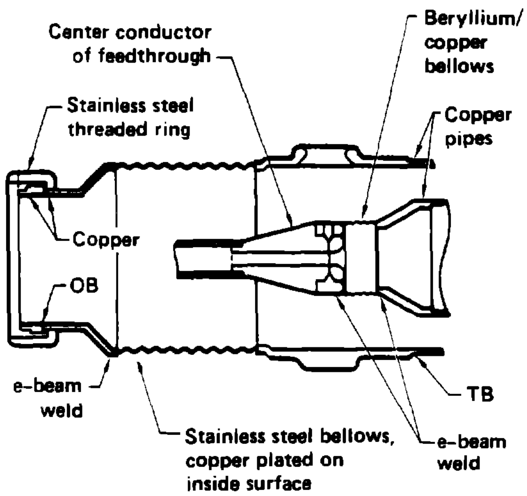


Section A-A

Inner Coax Pipe Support

Figure 7.

Since each coax assembly passed through the machine's liquid-nitrogen panels, we installed the bellows assemblies shown in Fig. 8 to accommodate contraction. The connections to the feedthroughs were



Coax Bellows Assembly

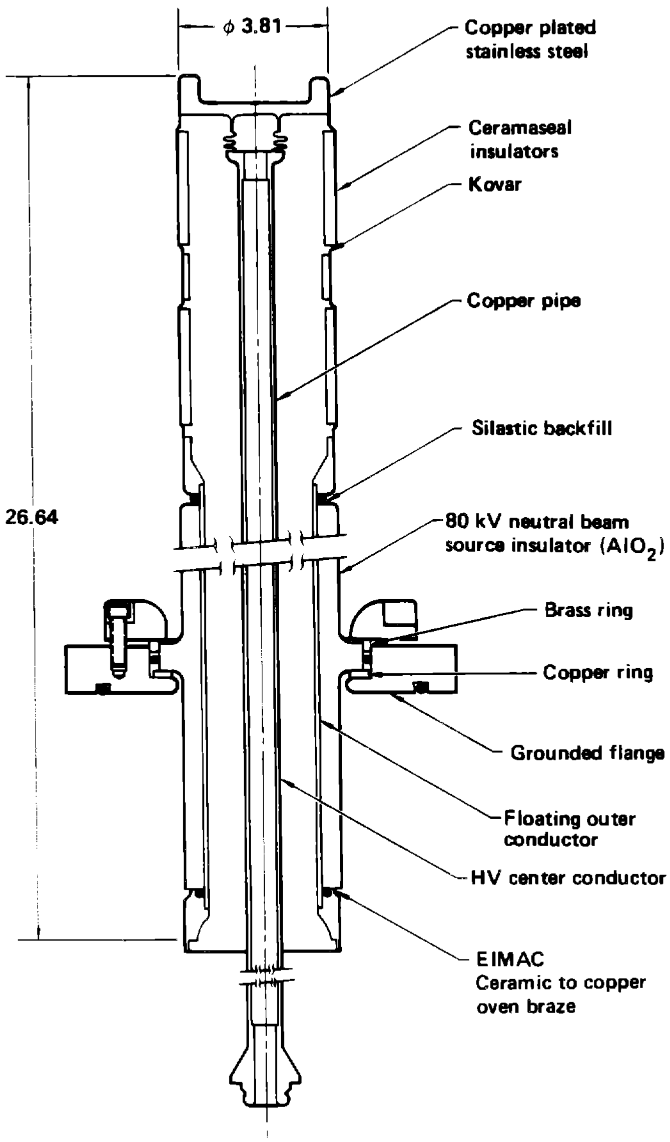
Fig. 8

also incorporated into these assemblies. The bellows that were available in the sizes required for the coax were a 4.119 ID stainless steel bellows and a 1.84-inch OD beryllium-copper bellows. Electron-beam welding was used to join the stainless steel bellows to the rest of the copper assembly. Because of the high RF currents that would flow on the inside of this bellows, it also had to be copper plated after assembly with 0.004 inches of copper. The amount of contraction expected on the outer coax was on the order of 3/8 of an inch, and so the bellows were installed in a compressed state to allow them to expand when the coax cooled. These bellows assemblies made the fabrication more complex, but they also proved to be helpful in taking up unexpected misalignments encountered during installation.

Feedthrough

The high-voltage RF feedthroughs used with the slot antenna are a triaxial design that we developed using some existing spare 80-kV neutral beam source insulators [2]. They also incorporate readily available Ceramaseal insulator breaks. A triaxial design was needed because both the inner and outer coax lines to the antenna could be driven to high RF voltages and currents. The design was driven mainly by time constraints, because there was not a similar type of feedthrough available on the market. There was also no attempt to make it match a certain impedance. The basic design parameters required that it hold 50 kV and 500 amps of RF on both the inner and outer conductors.

The final design, shown in Fig. 9, had several dissimilar material joint problems. The main vacuum seal on the bottom of the 80-kV source insulator is a special alumina ceramic-to-copper oven braze by Varian/EIMAC. The gap between the outer conductor and the source insulator was vacuum backfilled with silastic to reduce the electric field stresses that might develop in this gap and also to partly relieve the mechanical stresses that could be transferred to



Triaxial Feedthrough Assembly
Figure 9.

the delicate ceramic-to-copper EIMAC braze. The silastic backfill used has a lower temperature limit of -85°F. Since the connecting internal coax lines are made of copper, which is a very good thermal conductor, we placed double radiation shields inside the vessel wall to insulate the top of the coax from the liquid nitrogen panels. The Ceramaseal insulators available had a Kovar ring brazed to them. This required that the metal parts attached to them be stainless steel instead of the preferred copper. The joints were required to be vacuum tight and were made by e-beam welding. Since the stainless has a higher electrical resistance than the desired copper material, the top cap and stainless steel bellows assembly was copper plated on the inside where the RF currents would flow. The bellows was added to eliminate the long lever arm produced by the center conductor that could put a high stress on the Ceramaseal insulators. This stainless steel bellows was e-beam welded to its mating copper center conductor.

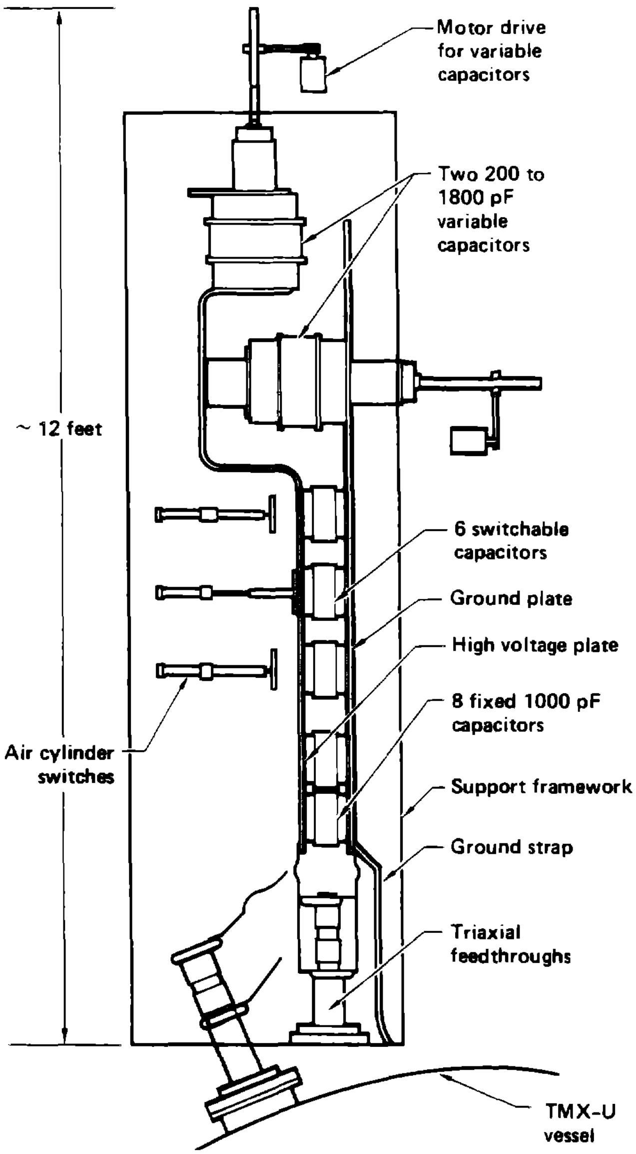
The connections to the outside of the feedthroughs were made with copper rings that clamped to the thick stainless steel rings of the feedthrough. The RF current connection, however, was made by placing RF wire gasket material near the Kovar-to-Ceramaseal insulator joint. To reduce the electrical field stress on the air side of the Ceramaseal insulators (rated at 40 kV DC each), we made the connecting rings with large 1/2-inch radii so that they would also act as corona rings. They protruded over the edges of the Kovar sleeves to shield the sharp edges where breakdown might occur.

Matching Network

The matching network of capacitors, shown in Fig. 10, is used to tune and match the transmitter power to the antenna and is located external to the vacuum vessel. It stands 12 feet high, is approximately 4.5 feet by 3 feet, and weighs approximately 3,400 pounds. It provided operation of the antenna system in the 2- to 5-MHz range.

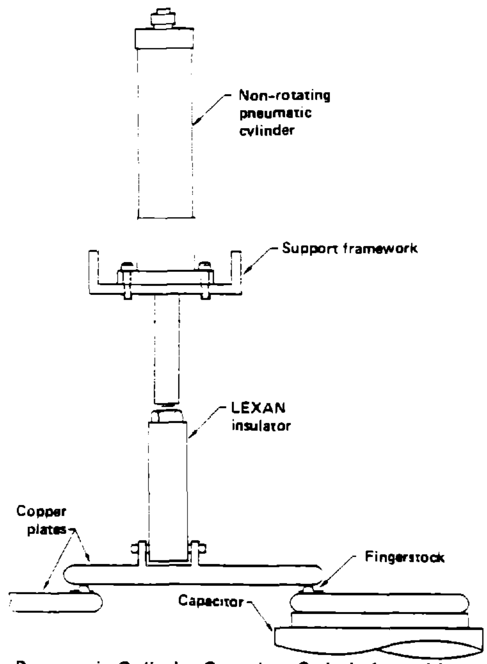
The matching network consists of two Jennings variable (100 to 1800 pF) capacitors, six Jennings fixed (1000 pF) capacitors that can be remotely switched into and out of the circuit, and room for up to ten Jennings fixed (1000 pF) capacitors that can be permanently bolted into the circuit. The top variable capacitor is connected in series with the incoming 50-ohm coax line from the transmitter. There can also be two fixed capacitors connected in parallel with this capacitor. The second variable capacitor, the six switchable fixed capacitors, and up to eight fixed capacitors are connected in parallel with the antenna. These parallel capacitors are mounted to two large 1/2-inch-thick copper plates that form the high voltage and ground plates. These plates weighed in at approximately 260 and 430 pounds, respectively. In practice we have only had to use three to four of the possible ten bolted-in fixed capacitors in the circuit. The same variable capacitor motor drive design, as used on our west 2 x 170 degree ICRH antenna, was used on the two variable capacitors in this matching network [3].

The supporting framework is made of stainless steel channels with Glastic insulators to electrically isolate the high voltage and ground plates. The ground plate is connected to the machine ground at only one location near the bottom of the plate. The connections from the matching network to the feedthroughs (shown in Fig. 10) are made with thin copper plates. They can be connected in two modes. The two outer feedthroughs are connected for the full-wave mode, or the single center feedthrough is connected to the plates for the half-wave mode.



Slot Matching Network Assembly
Figure 10.

To switch the six fixed capacitors we developed the design shown in Fig. 11. This system uses a pneumatic cylinder to move a copper plate that connects between the capacitor and main high-voltage plate. The air-operated cylinder is internally keyed to be nonrotatable and has a stroke of 3.5 inches. A 1.25-inch-diameter LEXAN insulator isolates the cylinder from the copper connecting plate. A good connection is made between the plates by using 5 inches of fingerstock rated at 47.2 amps per inch of length. The air pressure is varied to give the desired swtching speed. Copper bar stock is mounted to the plates to stop the switches when the fingerstock is properly compressed. In case of an air-pressure failure, the cylinders extend to short the capacitors. The electrical switches used to direct the air flow to the cylinders are also interlocked to extend the cylinder rod and short the capacitors in case of power failure or if an access panel is removed. These switches work quite well. They did require some reduction in weight of the connection plates and improvement of the connection between the insulator and the plate. Because of the impact forces and fatigue associated with making the plate connection, several insulators were tried before we settled on the LEXAN.



Pneumatic Cylinder Capacitor Switch Assembly
Fig. 11.

Conclusion

The use of a matching network external to the vacuum vessel has given us improved access to the capacitors and reliable voltage holding in the network without much fine tuning of the design. Having an external matching network made it necessary, however, to develop the high-voltage triaxial feedthroughs discussed. Care was also required in supporting, and electrically isolating, the high-voltage coax feed lines.

The slot antenna system has worked quite reliably from a mechanical point of view. We have experienced very few failures during the 13 months of operation of this antenna. Shielding of support insulators from the titanium gettering used in TMX-U has been the main improvement necessary on the system. The electrical operation of this slot antenna is described in the paper by S. W. Ferguson [4] and the physics results can be found in the two papers by W. F. Cummins [5,6].

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